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A SEARCH FOR COLLECTIVE PION PRODUCTION IN 2 GeV/NUCLEON HEAVY ION REACTIONS

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Abstract

The $\pi^{\pm}$ multiplicity distributions in ^{12}C and ^{16}O induced reactions in nuclear emulsion at 2 GeV/nucleon have been measured. The results are compared to a model in which we assume that only independent nucleon-nucleon scattering occurs. Such a model can explain the complete $\pi^{\pm}$ multiplicity spectra, only if we assume a very limited shadow effect, i.e. very few nucleons must be swept out of the nuclei during the time of overlap.

Introduction

Recently, some inclusive experiments have been performed to

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decide whether or not collective phenomena occur when pions are produced in heavy ion reactions [1-4]. Heavy ion beams (d-^{20}Ne) bombarding various heavy target nuclei at energies above 0.5 GeV/nucleon have been used in these experiments, and the main efforts have been concentrated on the following questions: 1. How large is the maximum momentum transferred to pions? 2. Can inclusive, double differential, pion production, cross sections be explained by a simple superposition of hadron-nucleus reactions or does collective production dominate?

In the experiments of Baldin et al. [1] (d+Cu $\rightarrow \pi^-$ + anything, ~ 7 GeV) and Schimmerling et al. [2] (^{14}N+Al $\rightarrow \pi^-$ + anything, 0.5 GeV/nucleon) there are indications that larger momenta are transferred to pions than can be accounted for by the kinematics of a nucleon-nucleon reaction, even if the Fermi motion is included. On the other hand Papp et al. [3] have shown that the$(E_\pi/p_\pi^2)d^2\sigma/d\Omega dp_\pi$ spectra of negative pions from d-, α- and ^{12}C-induced heavy ion reactions at 1-2 GeV/nucleon are very well reproduced by a simple overlap of nucleon-nucleus collisions after the introduction of Fermi momenta in the incident nucleus. However, a collective approach made by Mathis and Meng Ta-chung [5] seems to describe the same experimental data equally well. In this approach the interactions are assumed to take place between two "effective hadrons" with masses equal to νM where ν is the number of nucleons along the trajectory and M the nucleon mass.

In our experiment we have searched for signals from collective pion production in the $\pi^{\pm}$ multiplicity spectra of ^{12}C and ^{16}O reactions induced in electron sensitive emulsions at 2 GeV/nucleon. From dE/dx measurements of all charged particles we are able to obtain multiplicity distributions ($N_{\pi\pm}^{Em}$ distributions) close to the true $\pi^{\pm}$ multiplicity spectra. The $N_{\pi\pm}^{Em}$ spectra are compared to a model based primarily on nucleon-nucleon data, Woods-Saxon nucleon density distributions and straight line trajectories. The inelasticity of nucleon-nucleon scattering, Fermi motion and shadow effects are introduced and discussed.

2. Experimental Methods

In our experiment we used as target and detector Ilford K5 emulsions with a sensitivity of 17 grains/100 μm for a minimum ionizing particle. Two stacks were exposed one to a ^{12}C, the other to a ^{16}O beam both of 2.1 GeV/nucleon, at the Lawrence Berkeley Laboratory Bevatron. The flux was in each case $\sim 10^4$ cm^{-2}. The plates have been area-scanned twice and the mean free path for ^{12}C and ^{16}O in emulsion was found to be 14.9 ± 1.0 cm and 14.0 ± 0.7 cm respectively in good agreement with other experiments and estimations of reaction cross-sections [6]. 192 ^{12}C events and 495 ^{16}O events, completely randomly selected, have been found and used in our analysis.

Emission angles, Θ, and dip angles, φ, of all charged particles in an event have been determined by measuring x, y and z coordinates of the interaction vertex, three points on the beam track and three points on the track of the produced particle. The coordinates are corrected for the shrinkage factor of the emulsion, checked by thickness measurements before and after the development.

In order to classify the tracks into three particle groups (heavy prong producing particles (N_h), shower particles (N_s) and relativistic fragments) we performed dE/dx measurements according to table 1.

Table 1. Classification criteria and measurements performed on different prong categories.

	N_h	N_s	Relativistic fragments
Criteria:	$dE/dx >$ $1.4(dE/dx)_{min.}$ If $\theta \leq 5^o$ also a change in dE/dx along the track	$dE/dx \leq$ $1.4(dE/dx)_{min.}$	$dE/dx > 3(dE/dx)_{min.}$ $\theta \leq 5^o$ No change of dE/dx within the emulsion stack
Determination of dE/dx by:	Gap counting	Gap counting	Prel. charge. 2: Gap counting 3: Gap counting + opacity measurements. ≥4: Opacity measurements
Proton energy interval:	0-400 MeV	≥ 400 MeV	
Pion energy interval:	0-60 MeV	≥ 60 MeV	

A dip angle correction of the gap density is introduced:

$$G_\varphi = \frac{G_o}{\cos\varphi} \exp\left[g(k+d)\left(1-\frac{1}{\cos\varphi}\right)\right] \qquad (1)$$

where G_φ and G_o are gap densities for a track with a dip angle φ and 0^o respectively, g is the inverse mean gap length, k is the smallest visible gap length and d the grain diameter. This formula is discussed in Ref. 6.

A separation of the events into the three target groups H, CNO and AgBr has been made by using N_h multiplicities and target recoil tracks [6]. This classificiation gives, in each case, a percentage of events which is, within the statistical errors, in agreement with the percentage expected if known heavy ion reaction cross sections are used to calculate the target composition [6].

The charge of a relativistic fragment has been determined by opacity measurements with a photometer. Such measurements are described in detail in Ref. 7. The charge is estimated by determining the exponent x in the empirical formula:

$$Op = f(\beta) Z_{FR}^{x}, \tag{2}$$

where Op is the opacity, $f(\beta)$ is a function which is constant if only relativistic fragments are considered and Z_{FR} is the charge of the fragment. By using Li-fragments identified by gap density measurements and beam (^{12}C or ^{16}O) tracks we get:

$$x = \frac{\log \langle Op \rangle_{beam} - \log \langle Op \rangle_{Z=3}}{\log Z_{beam} - \log 3} \tag{3}$$

In both stacks x is found to be 0.70. The error of Z_{FR} determined in this way should always be within ± 1 unit.

On the completion of all these measurements, we can determine $N_{\pi\pm}^{Em}$, an approximation of the real number of charged pions, by the expression:

$$N_{\pi\pm}^{Em} = N_s - (Z_{beam} - \Sigma Z_{FR}) \ , \tag{4}$$

where the summation is made over all relativistic fragments with $Z \geq 2$ in a star.

Obviously, the parameter $N_{\pi\pm}^{Em}$ could differ from the actual number of charged pions. In the individual nucleon-nucleon scattering model, to be discussed next, we can, however, calculate $N_{\pi\pm}^{Em}$ as well as $N_{\pi^\pm}$.

3. Individual Nucleon-Nucleon Scattering Model

3.1 General Description

The individual nucleon-nucleon scattering model is based primarily on nucleon-nucleon cross section data in the energy interval 0.4 - 3.5 GeV, Woods-Saxon density distributions, an assumption of straight line trajectories and inelasticity distributions found in Monte-Carlo phase space generations of nucleon-nucleon events.

The total probability that we will register $N_{\pi\pm}^{Em}$ pions in a nucleus-nucleus event is given by:

$$P(N_{\pi\pm}^{Em}) = \sum P(n_i)P_{n_i}(\nu)P_{\nu}(N_{\pi\pm}^{Em}) \qquad (5)$$

where the summation is carried out over all sets of ν and n_i which give exactly $N_{\pi\pm}^{Em}$ registered pions. $P(n_i)$ is the probability that n_i beam nucleons will scatter, and $P_{n_i}(\nu)$ is the probability that one of these n_i nucleons will scatter exactly ν times. The probability distributions are obtained both by Monte Carlo calculations and wave mechanical calculations, where the Glauber idea of phase addition is used. $P_{\nu}(N_{\pi\pm}^{Em})$ is the probability that exactly $N_{\pi\pm}^{Em}$ charged pions are registered after ν reaction steps. In this determination Fermi motion in both nuclei is introduced for the first scattering step.

3.2 Determination of $P(n_i)$

The probability that n_i nucleons in a ^{12}C or ^{16}O beam nucleus will scatter is estimated by two methods, a Monte Carlo simulation and a wave mechanical treatment using the Glauber approximation.

3.2.1 Monte Carlo Calculations

The two interacting nuclei are represented by Woods-Saxon nucleon density distributions:

$$\rho(r) = \rho_o(\exp\,(r-b)/a \;\; +1)^{-1} \qquad (6)$$

with the parameters a = 0.55 fm
and $b = 1.1\ A^{1/3}$ (A = the nucleon number).

This distribution is used for all interacting nuclei i.e.
^{12}C, ^{14}N, ^{16}O, ^{80}Br and ^{108}Ag.

Furthermore, we assume that the nucleons have a "hard" core with a radius r_p i.e. the distance between the nucleon centra must be $\geq 2r_p$. An "interaction radius" r_i is used to determine the volume within which all target nucleons are hit by the incoming nucleon. A generation of proton-nucleus events is first made and the two parameters r_p and r_i are chosen in order to give agreement with the expected number of mean free paths of a nucleon in a nucleus:

$$\langle\nu\rangle = \frac{A\sigma_{pp}}{\sigma_{pN}} \qquad (7)$$

where σ_{pN} is the total p-nucleus cross section.

To estimate $\langle\nu\rangle$ we use $\sigma_{p\text{-}CNO}$ = 394 mb and σ_p-AgBr = 1760 mb, values which can be determined from experimental reaction cross sections, σ_R, [6] and the σ_{tot}/σ_R ratio as calculated in Ref. 8. This gives $\langle\nu\rangle$ = 1.7 and 2.5 respectively in the GeV region. Reasonable agreement with these values is found in the generation of proton-nucleus events if r_p = 0.6 fm and r_i = 1.05 fm are used, i.e. a r_p value which is somewhat larger than the repulsive radius (0.3 - 0.5 fm) and a r_i value which is somewhat smaller than the radius associated with the elementary nucleon-nucleon cross section at 2 GeV (σ = 46 mb $\Rightarrow$ r_i = 1.21 fm). Smaller variations of r_p and r_i will however affect the final pion multiplicity distributions very little. ^{12}C and ^{16}O-induced events are now generated using the above-mentioned values of r_p and r_i.

We must in this type of calculations consider the effects of a possible nucleon density decrease along the paths of the beam nucleons. Such a decrease will subsequently be referred to as a "shadow" and this effect is introduced in the calculations simply by assuming that a certain percentage of nucleons along the reaction tube, of radius r_i, is swept away before the next nucleon enters.

Fig. 1 shows in the case of ^{16}O-AgBr reactions, how the $P(n_i)$ distributions are shifted towards lower $\langle n_i \rangle$ when a shadow is introduced,

In Fig. 2 we show $P(n_i)$ for ^{16}O-CNO and ^{16}O-AgBr reactions on the assumption that no shadow appears and compare these distributions with probability calculations using the optical approach to be discussed next.

3.2.2 Wave Mechanical Calculations

The dependence of the phase shift, χ, on the impact parameter $\bar{b}$ can be written:

$$\chi(\bar{b}) = \frac{2\pi}{k} f(0)T(\bar{b}) \quad , \qquad (8)$$

where k is the wave number, f(0) the forward scattering amplitude and:

$$T(\bar{b}) = B \int_{-\infty}^{+\infty} \rho_B(\bar{b},z)dz \quad , \qquad (9)$$

(z beam direction), represents the transparency function.

For the heavy ion reaction A+B the mean value of $T(\bar{b})$ is given by:

$$\langle T(\bar{b})\rangle = \frac{\int T(\bar{b}+\bar{s})\ \rho_A(\bar{s})\ d^2s}{\int \rho_A(\bar{s})\ d^2s} \quad , \qquad (10)$$

where $\bar{b}+\bar{s}$ is the position vector representing a beam nucleon in the plane transverse to $\bar{z}$. For projectile and light target nuclei (C,N,O) we choose gaussian density distributions:

$$\rho(r) = A\exp(-r^2/a^2) \ , \qquad (11)$$

where a is connected to the rms radius of the nucleus through:

$$A = r_{rms}/\sqrt{3/2}$$

For a heavy target nucleus (Ag,Br) a two parameter Fermi type density distribution is used:

$$\rho_B(r) = \rho_o\left[1 + \exp\ \left\{(r-c)4\ln 3/t\right\}\right]^{-1} \ , \qquad (12)$$

where c and t are the half density radius ($1.07A^{1/3}$) and the skin thickness (2.4 fm), respectively.

The forward scattering amplitude is related to the total nucleon-nucleon cross section (σ) by the optical theorem:

$$f(0) = \frac{ik\sigma'}{4\pi}; \quad \sigma' = \sigma\left(i + \frac{\mathrm{Re}\ f(0)}{\mathrm{Im}\ f(0)}\right) \qquad (13)$$

and thus we get:

$$\chi(\bar{b}) = \frac{\sigma'}{2}\langle T(\bar{b})\rangle \qquad (14)$$

The probability that one incident nucleon will scatter is

$$P_1(\bar{b}) \sim 1 - \exp\left[2\mathrm{Re}\ i\ \chi(\bar{b})\right] \qquad (15)$$

and the probability that exactly n_i nucleons out of A shall collide:

$$P_{n_i}(\bar{b}) = \binom{A}{n_i}\left[P_1(\bar{b})\right]^{n_i}\left[1-P_1(\bar{b})\right]^{A-n_i} \qquad (17)$$

The probability that exactly n_i incident nucleons shall scatter is now given by integration over the impact parameter. This has been done numerically and the results for ^{16}O reactions induced in CNO and AgBr are shown in Fig. 2. No shadow effect has been introduced in the above calculations, so when the comparison is made between the two different $P(n_i)$ predictions in Fig. 2, the Monte-Carlo results of "no shadow" calculations are used. In the case of ^{16}O-CNO reactions the two calculations give very similar $P(n_i)$ distributions. For ^{16}O-AgBr reactions there are some differences, but these will affect the final $\pi^{\pm}$ multiplicities so little that we subsequenly used only the Monte-Carlo predictions.

3.3 Determination of $P_{n_i}(\nu)$

The probability that a beam nucleon scatters ν times in the target is taken from the Monte-Carlo calculation. In Fig. 3 we show how $P(\nu)$ varies with n_i in the case of ^{16}O-AgBr reactions for $1 \leq \nu \leq 5$ (in the 6^{th} scattering the probability of producing pions can be completely neglected). It is obvious that different $p_{n_i}(\nu)$ distributions for $1 \leq n_i \leq A$ must subsequently be used.

3.4 Determination of $P_\nu(N_{\pi\pm}^{Em})$

The next step in our calculation is to find the expected probability distribution of charged pion multiplicities after the ν^{th} nucleon-nucleon scattering step.

Since we consider Fermi motion and inelasticity, it is necessary to use $\pi^{\pm}$ multiplicity distributions of nucleon-nucleon scattering in the energy interval 0.4 - 3.5 GeV. We have estimated such distributions for each 0.4 GeV bin by using cross section data from Ref. 10 for pp and pn reaction channels (also elastic), giving a contribution > 0.1 mb somewhere in the energy bin. For np and nn reactions we have simply assumed that these have the same cross sections as the corresponding pn and pp channels. The Fermi momenta in both participating nuclei are introduced in the first reaction step through Fermi momentum spheres with radii 235 MeV/c. This may be a crude description, but any other more sophisticated form of the Fermi momentum distribution will not alter our $\pi^{\pm}$ multiplicity distributions noticeably.

The energy distributions of the nucleons after the first reaction step were constructed by Monte Carlo phase space generations of events from the FOWL programme [9] for inelastic channels. In the case of elastic scattering the summation of experimental $d\sigma/dt$ distributions made in Ref. 10 were used. In fig. 4 we show the energy distributions of the nucleons after an incident nucleon (2 GeV) has scattered 1-4 times.

For each reaction step (ν = 1,2,3,4, $\geq$ 5) we get in this way the $P_{\nu}(N_{\pi\pm})$ distribution. It is, however, not possible in the experiment to register exactly the number of pions in each event and in order to get a parameter which corresponds to $N_{\pi^{\pm}}^{Em}$ given in eq. (4) we introduce the following corrections in the calculations:

1. The slow pions ($E_{\pi} \lesssim$ 60 MeV) will be registered as heavy prongs and not as shower prongs, which means that $N_{\pi\pm}^{Em}$ will be one unit lower than $N_{\pi\pm}$ if one slow pion is emitted. ($N_{\pi\pm}^{Em} = N_{\pi\pm} - 2$ is negligible).
To introduce this correction we use once again the FOWL phase space generation of events [9] to find out the amount of slow pions in each reaction channel.

2. In reaction channels with two protons in the final state,

both protons may have energies above or below 400 MeV. In this case the two protons will be registered as shower prongs or heavy prongs, and the $N_{\pi\pm}$ pions will be changed into $N^{Em}_{\pi\pm} = N_{\pi\pm} \pm 1$. The frequency of such events is given by the energy distributions from the FOWL generation [9] for inelastic channels, and by experimental $d\sigma/dt$ distributions for elastic reactions (i.e. $pp \rightarrow pp$)[10]. The dominating effect of this correction will be $N^{Em}_{\pi\pm} = N_{\pi\pm} + 1$, since this effect dominates above 1 GeV, where the majority of the individual nucleon-nucleon scatterings take place.

3. Charge exchange reactions may also give $N^{Em}_{\pi\pm} = N_{\pi\pm} \pm 1$. In the case of elastic charge exchange reactions, $pn \rightarrow np$ or $np \rightarrow pn$, some experimental cross sections exist [10] and these are used. For the inelastic channels we simply assume that charge exchange occurs in 50% of the scatterings.

The effects on the multiplicity distributions by the introduction of these three "emulsion corrections" are shown in Table 2.

Table 2: Probabilities for the production of $N_{\pi^\pm}$ pions and $N^{Em}_{\pi^\pm}$ registered pions from a nucleon-nucleon scattering at 0.5 and 2 GeV. The effects of the Fermi motion in both reacting nuclei are also presented.

Energy		$N_{\pi^\pm}$, $N^{Em}_{\pi\pm}$ -1	0	1	2	3	4
0.5 GeV	$P(N_{\pi\pm})$ %		85.4	14.6			
	$P(N^{Em}_{\pi\pm})$ %	43.3	50.5	6.1	0.1		
2 GeV	$P(N_{\pi\pm})$ %		58.6	32.0	8.7	0.7	
	$P(N^{Em}_{\pi\pm})$ %	1.0	57.5	22.7	16.1	2.5	0.2
	Including Fermi motion	1.9	55.9	23.9	15.6	2.4	0.3

The probability for a negative number of registered pions is large at low nucleon energies. The relative fraction of scatterings at these energies is, however, small. The $P(N_{\pi\pm}^{Em})$ values at 2 GeV is, on the other hand, typical for the multiplicity broadening expected if a nucleon-nucleon model is a useful description of the heavy ion events.

Apart from the occurance of negative registered $\pi^{\pm}$ multiplicities, we can notice an increase in the probability of registering two charged pions and a corresponding decrease of registering one charged pion. This phenomenon will be noticeable in all our final calculated $P(_{\pi\pm}^{Em})$ distributions.

The total probability distribution $P(N_{\pi\pm}^{Em})$ is now found by adding up all products $P(n_i)P_{\pi_i}(\nu)P_\nu(N_{\pi\pm}^{Em})$ that give exactly $N_{\pi\pm}^{Em}$ registered pions.

4. Results and Discussion

The experimental $N_{\pi\pm}^{Em}$ distributions in ^{12}C and ^{16}O reactions induced in the target groups H, CNO and AgBr are presented in Figs. 5 and 6. The curves are the results from the individual nucleon-nucleon scattering model calculations. In all cases these distributions are normalized to the experimental number of events with $N_{\pi\pm}^{Em} \leq 4$, where we can expect a reasonable agreement, irrespective of whether collective production of pions exists or not.

For $^{12}C(^{16}O)$ - H reactions we have used $P(N_{\pi\pm}^{Em})$ distributions obtained in p - $^{12}C(^{16}O)$ events. The nucleon-nucleon scattering model adjusted to the observed parameter $N_{\pi\pm}^{Em}$ reproduces the experimental multiplicity distributions in ^{12}C-H and ^{16}O-H events very well. Without the corrections and the multiple scattering effect the disagreement would be considerable (Table 2).

For heavy ion reactions we have introduced a shadow effect in the calculations, which takes into consideration the nucleon density decrease upstream of the trajectory of an incident nucleon. We see from Figs 5 and 6 that we cannot assume a complete shadow to exist for $^{12}C(^{16}O)$ - CNO reactions if we want to explain the frequency of large $N_{\pi\pm}^{Em}$ events. It seems to be necessary to neglect the shadow completely in order to reproduce these parts of the spectra, especially if we bear in mind that the reabsorption of pions, which should decrease $\langle N_{\pi\pm}\rangle$ somewhat has not been introduced in the model. Neglecting the shadow is synonymous with regarding the nucleus-nucleus collision as an overlap of nucleon-nucleus reactions with the introduction of Fermi momentum. This type of approach which has shown good agreement with experimental results, both in pion multiplicity experiments [11] and in differential cross-section experiments [3,4] seems to be valid also for our CNO multiplicity distributions.

If there exist signals from collective production in our data, these should be most pronounced in $^{12}C(^{16}O)$-AgBr events. We can, however, also reproduce the experimental $P(N_{\pi\pm}^{Em})$ distributions of AgBr events with the model if we assume the shadow effect to be small, or negligible, since the absorption of pions should be important here.

In Fig. 7 we present the ^{16}O-AgBr multiplicity data together with the model prediction under the assumption that 50% of the nucleons are swept away from the target nucleus before a subsequent projectile nucleon enters the system. In this case the curve is normalized to the total number of pions. By this comparison, we just want to further stress, that by an appropriate choice of the "density decrease parameter", the complete experimental $\pi^{\pm}$ multiplicities can be reproduced by the independent nucleon-nucleon model.

In Fig. 8 we give an example of the difference between the $\pi^{\pm}_{Em}$- and the $\pi^{\pm}$ multiplicity distribution. In this case the calculations have been performed for ^{12}C-AgBr reactions on the assumption that no shadow effect exists.

Conclusions

An independent nucleon-nucleon scattering model can only under certain assumptions explain the experimentally obtained $\pi^{\pm}$ multiplicity distributions in ^{12}C and ^{16}O induced reactions in nuclei at 2 GeV/nucleon. In order to reach the experimental frequencies of large $\pi^{\pm}$ multiplicity events we have to assume that only a very small part of the hit target nucleons are swept out from the reaction volume during the time of overlap. If a large shadow effect is introduced, the frequency of large $\pi^{\pm}$ multiplicity events can, however, only be explained if some collective pion production process is present.

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References

1. A.M. Baldin, S.B. Gerasimov, H. Guiordenescu, V.N. Zubarev, L.K. Ivanova, A.D. Kirillov, V.A. Kuznetsov, N.S. Moroz, V.B. Radomanov, V.N. Ramzhin, V.S. Stavinskii and M.I. Yatsuta, Sovj. J. Nucl. Phys. 18, 41 (1974).

2. W. Schimmerling, K.G. Vosburgh, K. Koepke and W.D. Waler, Phys. Rev. Lett. 33, 1170 (1974).

3. J. Papp, J. Jaros, L. Schroeder, J. Staples, H. Steiner, A. Wagner and J. Wiss, Phys. Rev. Lett. 34, 601 (1975).

4. K. Nakai, J. Chiba, I. Tanihata, S. Nagamiya, H. Bowman, J. Ioannou and J.O. Rasmussen, Proc. VIIth Int. Conf. on High Energy Phys. and Nucl. Structure, Zürich (1977).

5. H.B. Mathis and Meng Ta-chung, Free University of Berlin, Preprint FUB HEP 77/11 (1977).

6. B. Jakobsson and R. Kullberg, Physica Scripta 13, 327 (1976).

7. E. Higón, Thesis, University of Valencia (1977).

8. S. Barshay, C.B. Dover and J.O. Vary, Phys. Rev. 11, 360 (1975).

9. FOWL-program. CERN-Program Library.

10. E. Bracci, J.P. Droulez, E. Flaminio, J.D. Hansen and D.R.O. Morrison,
CERN-HERA-Report 73-1 (1973).
O. Benary, R. Price and G. Alexander,
UCRL-Report 20000 NN (1970).

11. J.P. Vary,
To be published. Private communication.

Figure captions

1. The probability that n_i beam nucleons will scatter on different assumptions about the shadow effect in ^{16}O-AgBr collisions at 2 GeV/nucleon.

2. The probability that n_i beam nucleons will scatter in ^{16}O-CNO and ^{16}O-AgBr collisions at 2 GeV/nucleon.
Method 1 - Wave mechanical calculations.
Method 2 - Monte-Carlo calculations.

3. The probability that one out of n_i scattered nucleons will scatter exactly ν times in the target nucleus.

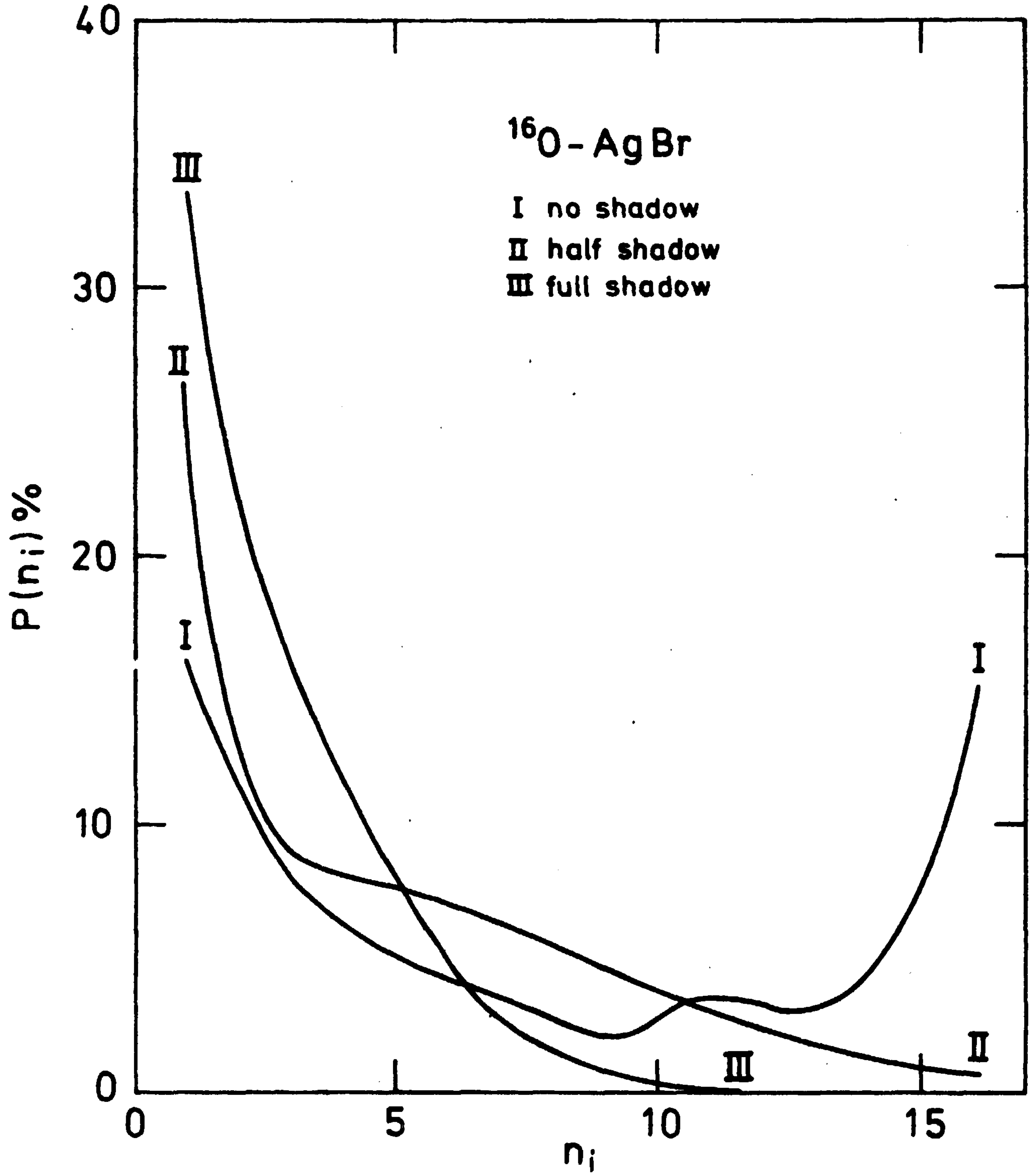
4. The energy distribution of nucleons with an incident energy of 2 GeV after ν scatterings.
The figures above the arrows give the probability for a nucleon to have $E < 0.4$ GeV.

5. Pion multiplicity distribution in ^{12}C-H, ^{12}C-CNO and ^{12}C-AgBr reactions at 2 GeV/nucleon. The curves exhibit the results of the independent nucleon-nucleon model.

6. Pion multiplicity distributions in ^{16}O-H, ^{16}O-CNO and ^{16}O-AgBr reactions at 2 GeV/nucleon. The curves exhibit the results of the independent nucleon-nucleon model.

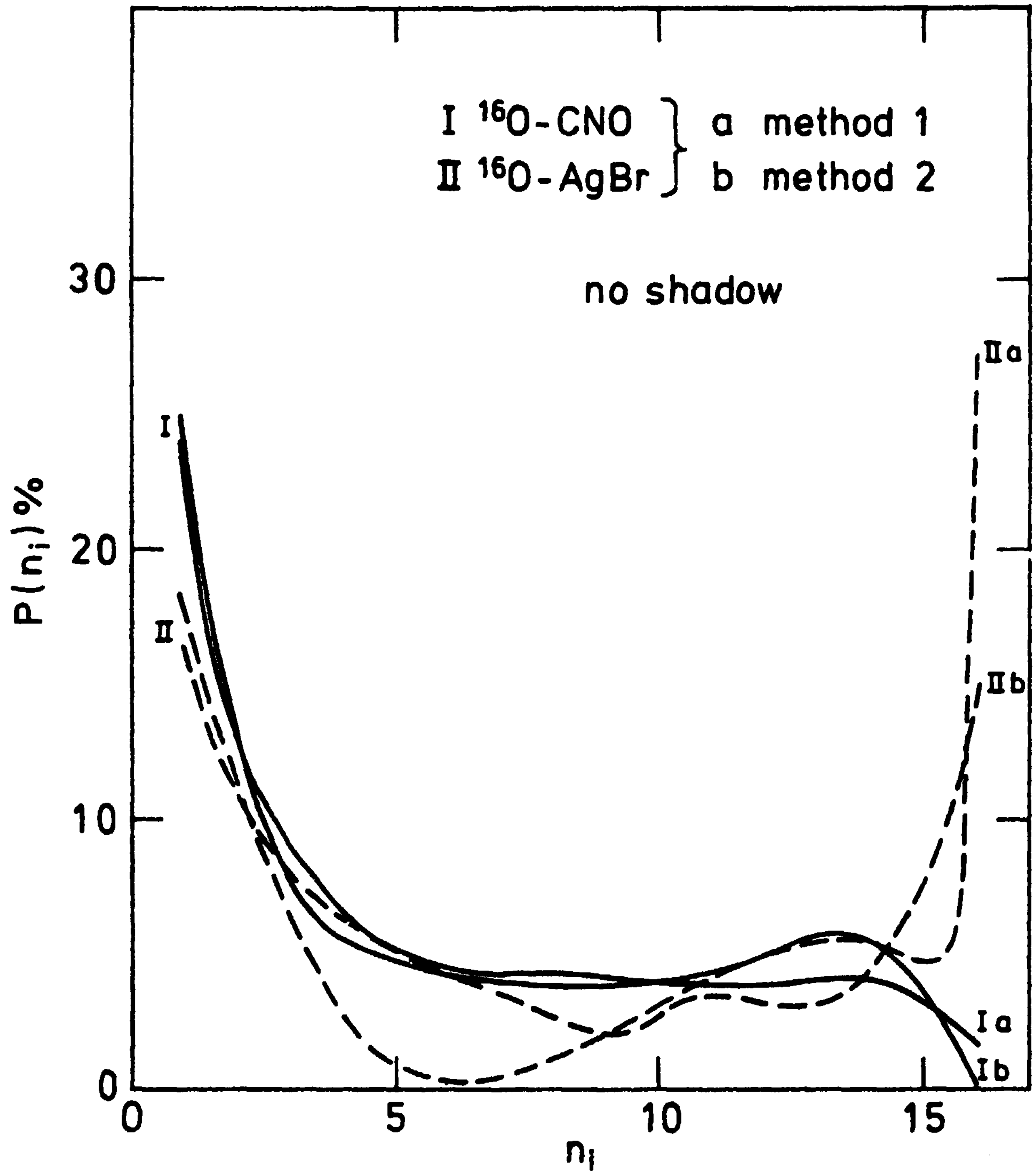
7. Pion multiplicity distribution of ^{16}O-AgBr events at 2 GeV/nucleon compared to the predictions from the independent nucleon-nucleon scattering model on the assumption that a "50% shadow effect" exists.

8. Comparisons between $P(N_{\pi\pm})$, (a), and $P(N_{\pi\pm}^{Em})$, (b), distributions from the independent nucleon-nucleon model calculations for ^{12}C-AgBr, without any shadow effect.



^{16}O - AgBr
I no shadow
II half shadow
III full shadow
P(n_i) %
n_i
0
5
10
15
10
20
30
40
I
II
III

FIG. 1



I ¹⁶O-CNO
II ¹⁶O-AgBr
a method 1
b method 2
no shadow
P(nᵢ)%
nᵢ
30
20
10
0
0
5
10
15
I
II
IIa
IIb
Ia
Ib

FIG. 2

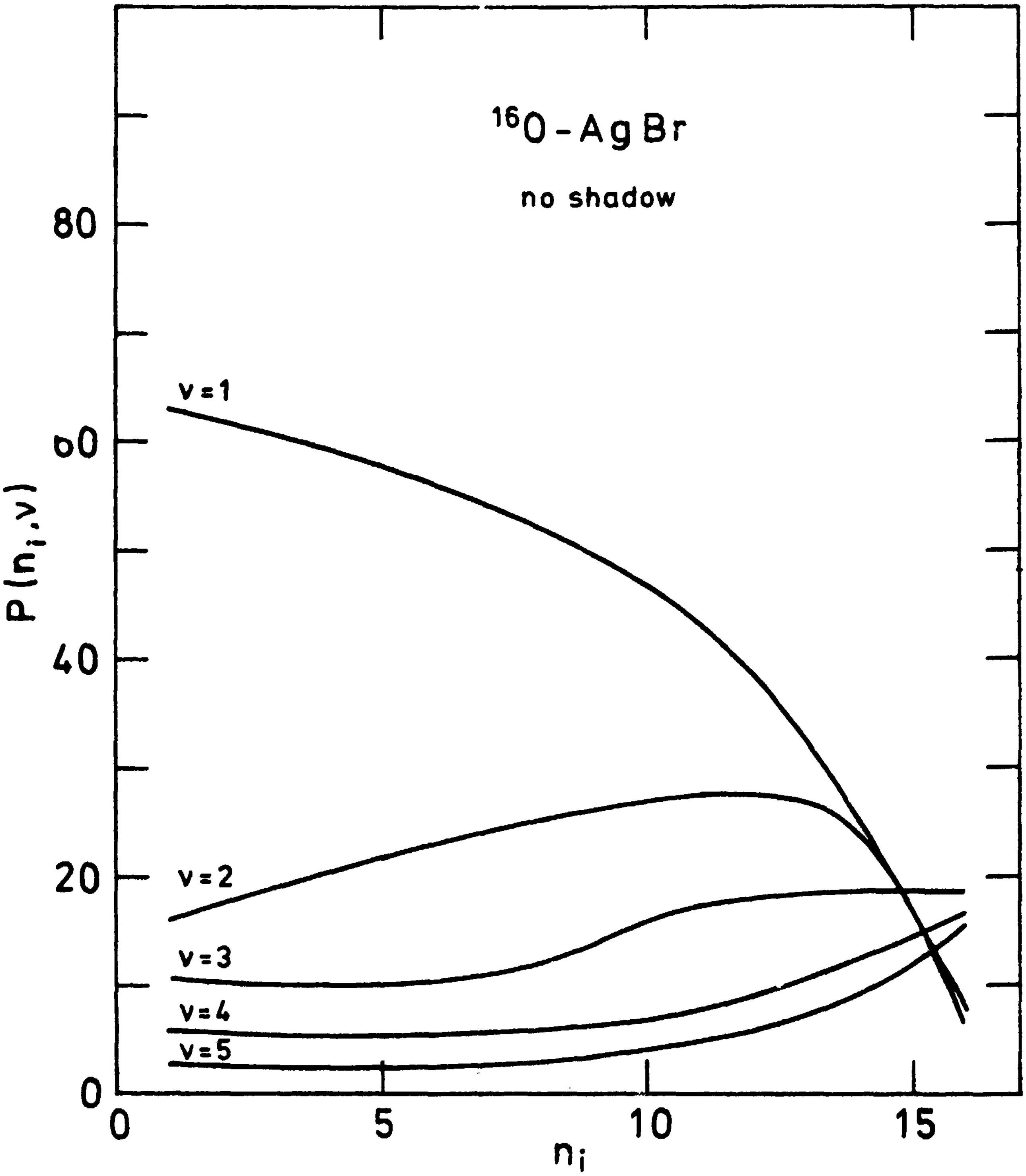


FIG. 3

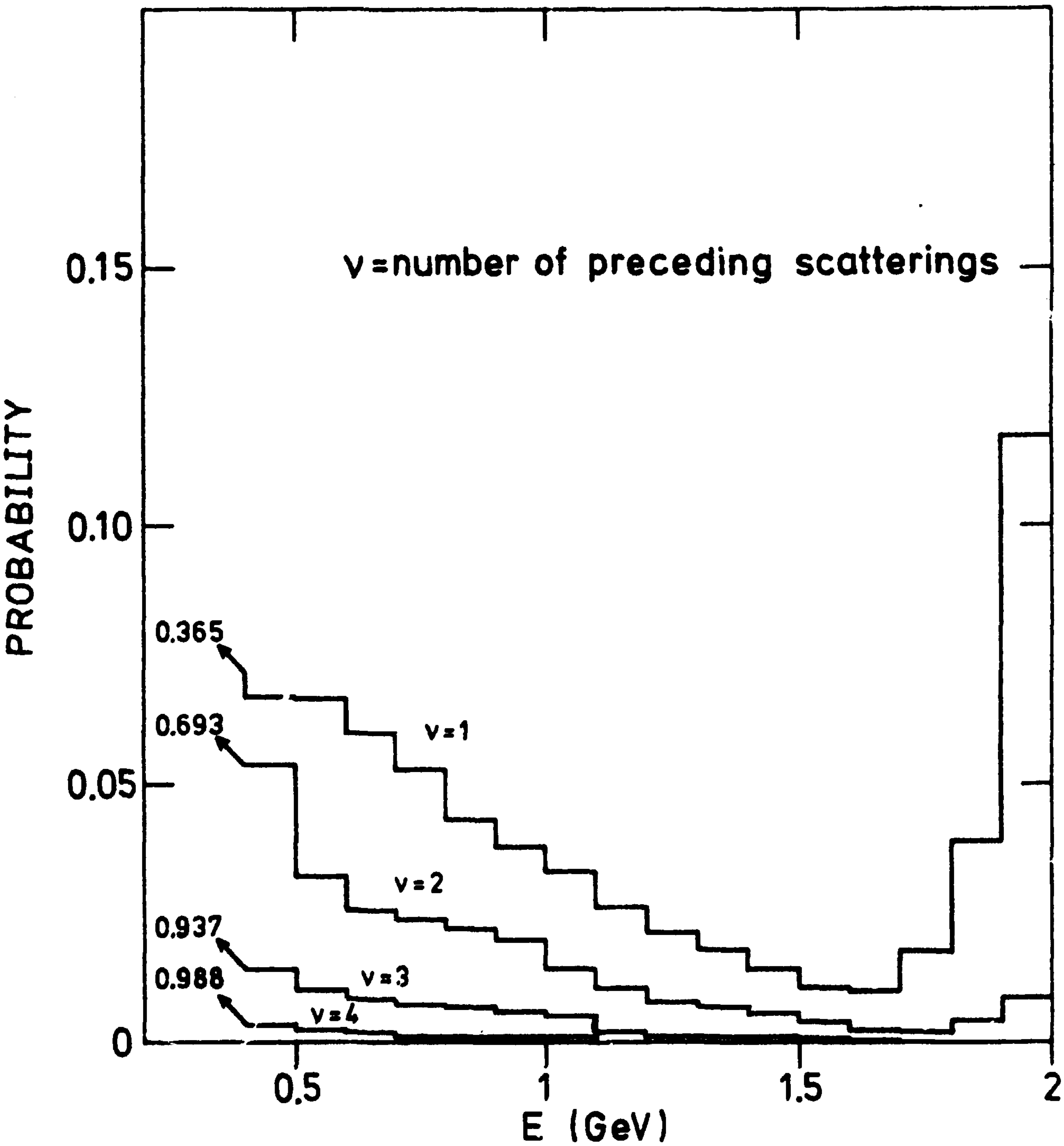
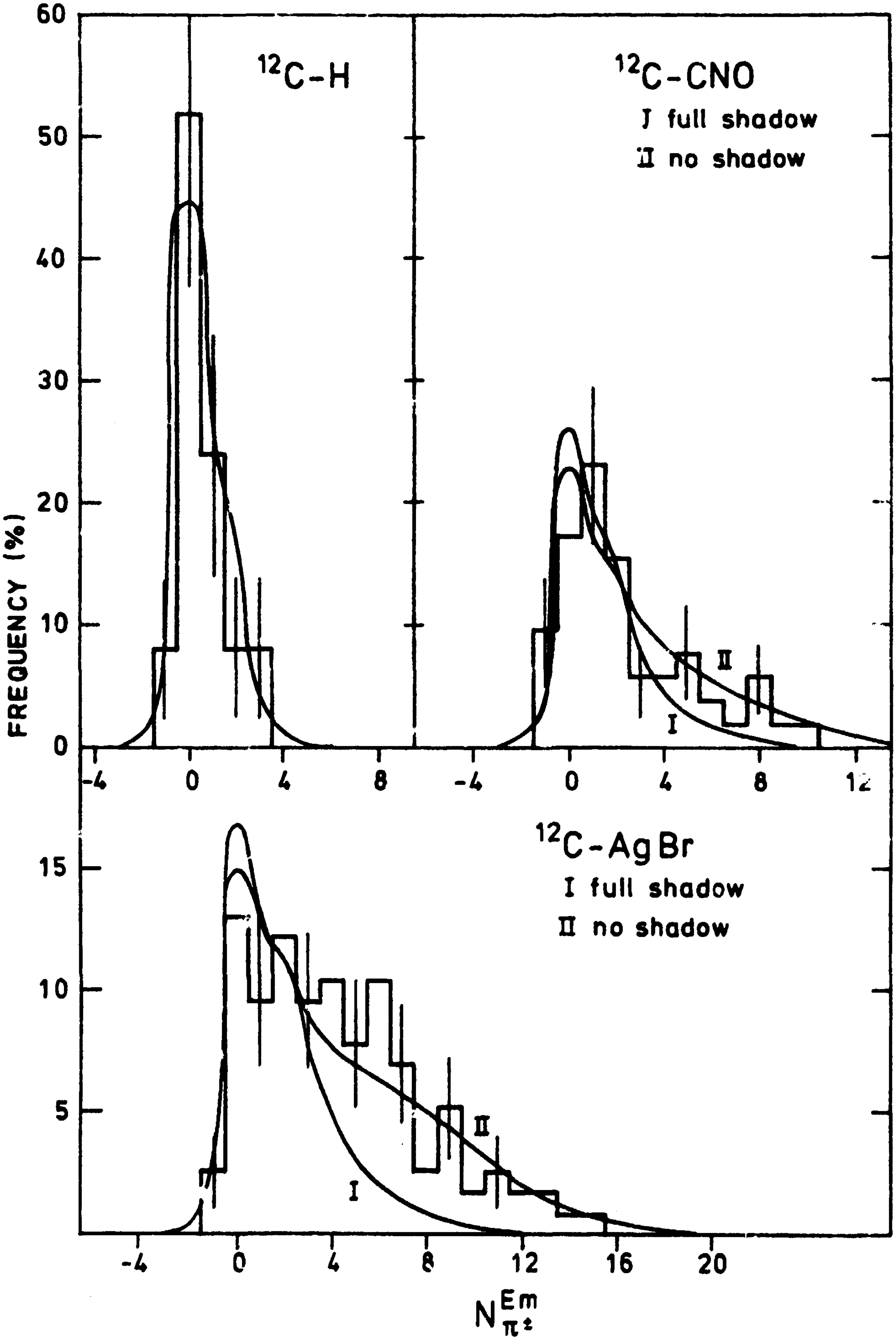
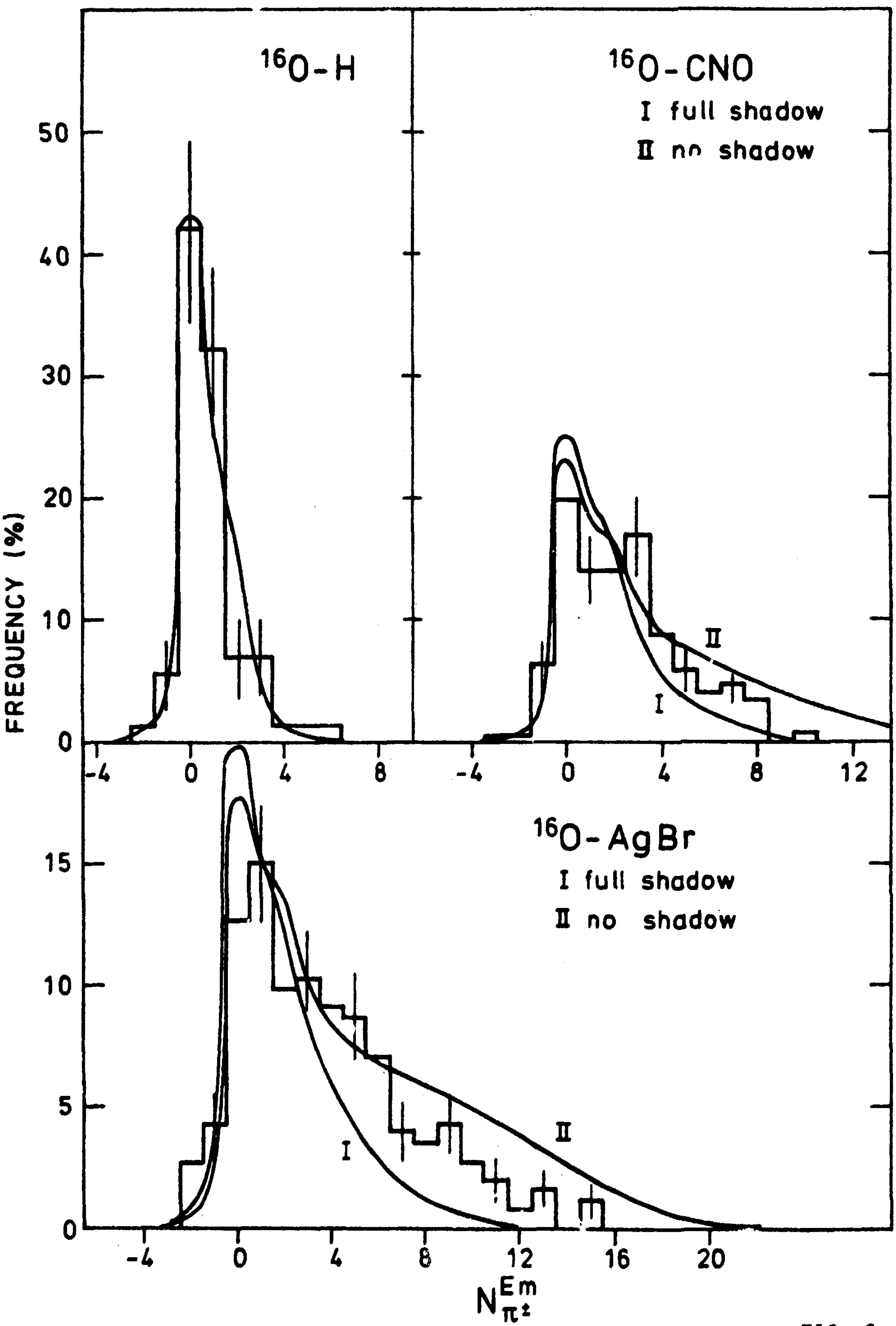

ν=number of preceding scatterings
PROBABILITY
0.15
0.10
0.05
0
0.365
0.693
0.937
0.988
ν=1
ν=2
ν=3
ν=4
0.5
1
1.5
2
E (GeV)

FIG. 4



^{12}C-H
^{12}C-CNO
I full shadow
II no shadow
^{12}C-AgBr
I full shadow
II no shadow
FREQUENCY (%)
$N_{\pi^\pm}^{Em}$

FIG. 5



^{16}O-H
^{16}O-CNO
I full shadow
II no shadow
^{16}O-AgBr
I full shadow
II no shadow
FREQUENCY (%)
$N_{\pi^{\pm}}^{Em}$
I
II

FIG. 6

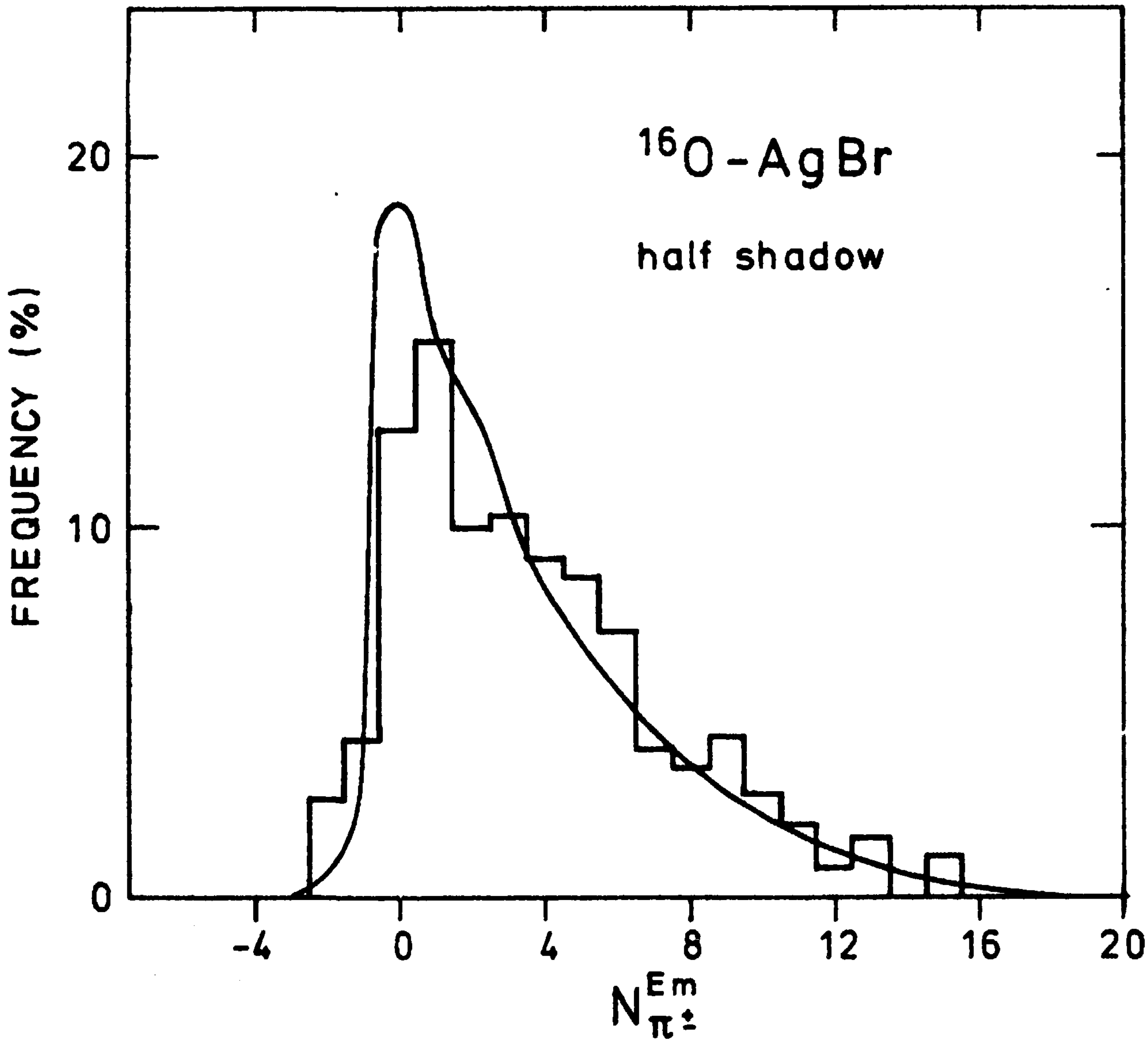


FIG. 7

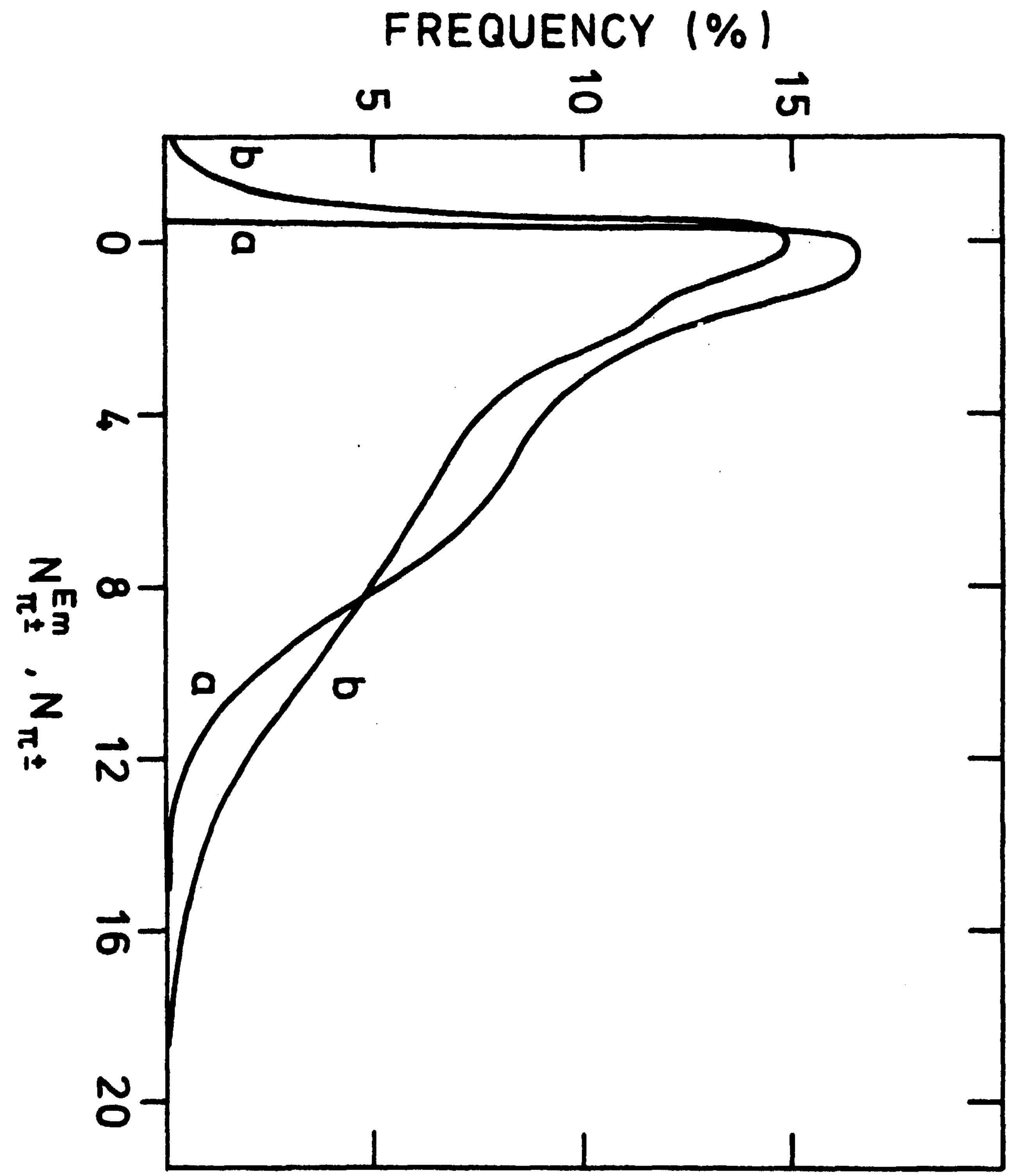


FIG. 8